
An empirical model for mine-blast loading

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ABSTRACT

The anti-vehicular landmine threat has increased greatly since 2005. It has now become one of the important causes of vehicle losses in combat operations, and a major threat to vehicle occupants in many countries. Experimental and numerical studies of buried charge effects on structure and the measurement of the loading produced by landmines become important topics to study. These types of researches are done to support the development of improved vehicle protection to resist blast from landmines and Improvised Explosive Devices (IED's). Since it is a very challenging task to model explosive detonation, shock wave formation and propagation as well as interaction with structures from first principles, a phenomenological approach was investigated. Many non-impulsive pressure models were investigated to model the damage on a plate from a blast landmine. The assumption that the loading generated by the blast is purely impulse is critically investigated and rejected. A new non-impulsive time-distribution pressure model is then proposed. The outputs of the new pressure model were validated using experimental data from 6 kg TNT experimental tests on plate flat.

Keywords: blast landmines, modelling, vehicle protection.

1.0 INTRODUCTION

Landmines and anti-vehicular mine blasts are among the most important threats for many military forces [1-7]. For this reason, protection systems have been designed and developed in the last few decades. A series of new ideas and concepts emerged from these researches. These include new ways of protecting and stiffening the hull of the vehicle, suspension systems for the occupants, etc. The testing of these new designs requires an important deployment of resources and thus, can be very costly. Hence, a numerical approach becomes a very useful tool for design purposes because it allows more flexibility and an easier implementation than a full-fledged experimental program. The numerical approach however suffers from several drawbacks in the mine blast simulations. First, it is a very challenging task to model this phenomenon from first-principles that is including the detonation of the explosive, the formation of the shock wave and the blast-soil interaction. The variability in the soil properties and its effect on blast render the task even more problematic because this effect cannot be characterized precisely. Therefore, a phenomenological approach seems more suitable such as the Southwest Research Institute (SwRI) Westine model [8], a computer program that could predict the response of floor plates to a land mine explosion. In the process, SwRI developed a load model from a classical non-dimensional analysis and then performed a series of small-scale experiments to validate the model. The Westine model was used successfully in many applications involving mostly rigid body motion. For example, the effect on the occupants due to the motion of a vehicle subjected to a mine blast has been studied [9-13]. In those applications, the model seems to provide accurate predictions. This is confirmed by examining the experimental results where the total impulse was measured for different soil and different configurations. The Westine model represents the 50th

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percentile for the total impulse imparted on a plate [13, 14]. The deviation in the results can be related mostly to the soil properties and/or variation in the TNT loading in this type of environment. On the other hand, the same model was used to study the local plate deformation (meshed using shell elements) [9] and over-predicted the deflection by approximately 35-40 %. A correction factor was then introduced to scale down the impulse to get the right deflection, assuming that this discrepancy was due to uncontrolled parameters such as soil properties and imperfect detonation. It is noteworthy here to state that this approach was based, just like for the rigid motion studies, on the assumption that the loading on the plate is impulsive, that is the duration of the loading is much shorter than the typical reaction time of the plate. This seems very plausible given the time of the mine explosion event, on the order of 4-5 ms, and the fact that the plate reaches its highest velocity at approximately 1-2 ms. In this work, this hypothesis is revisited and critically investigated.

The main assumption, on which this study is based, is that for local deformations and typical material found on a vehicle (RHA plate); the mine loading is not impulsive. Rather, it lasts for certain time duration, shorter than the time for the whole blast event (around 6 ms, including the structural response). Thus, the loading is applied (on solid elements) as a pressure-time history rather than as an initial velocity (assuming an impulsive loading which is usually applied on shell elements), as was previously done. It is demonstrated in this study that this leads to much more accurate results than the impulsive method using velocity.

2.0 EXPERIMENTAL SETUP AND RESULTS

A common experimental method to assess the output of buried explosive charge consists in measuring the total impulse transmitted to a given structure. The Army Research Laboratory uses the Vertical Impulse Measurement Facility (VIMF) to study effects of buried charge loading on structures [14]. In VIMF, a large-scale piston is used to mount deformable structures at the end of the vertical shaft. This design makes possible the study of the effect of full-scale mines on full-scale structures while measuring the net vertical momentum transfer to the shaft. This is a powerful tool to study the relationship between structural deformation and gross vehicle acceleration.

DRDC has been using several large and small scale facilities in the past to assess buried charge loadings [3, 9]. A similar implementation of a flat plate attachment to a test rig fixed to the ground, used by DRDC, has also been used in Meppen, Germany, to study the response of various flat plate thicknesses to landmine blast. The ONAGER used at DRDC Suffield consisted in a pendulum type device to measure global impulse of buried mine [15]. One of the main purposes of the ONAGER pendulum was to study the effect of soil conditions on the total momentum transfer to a vehicle. In its study of mine effects on structure, DRDC-Valcartier has been using different test setups for characterizing buried charge loadings and assessing material performance. The test setup used consisted of free flying simple frames, on which material coupons could be installed to monitor both the global (complete setup) and local (material coupon) reactions. Since this setup did not provide a direct measurement of the loading on the plate, more recently, DRDC Valcartier has initiated a research program to develop a large scale experimental method to measure the distribution of the specific impulse generated by an explosive charge buried in different soil types and under various conditions and to develop enhanced numerical models for the loading generated by these threats [16].

The frame setup shown in Figure 1 was designed to accommodate material coupon sizes and boundary conditions from different requirements. The design of the frame is an iteration of previous setups used by Defence Research and Development Canada (DRDC) Valcartier and has been done to provide better versatility and control over the target sizes, boundary conditions of the target and better monitoring of the target back face for observing the local deformation and material behaviour subjected to buried charge loadings. The impulse frame can be described as a "free motion" setup as its motion is not controlled by any mechanical guides or restraints and only depends on gravity for deceleration. The decision to use a "free flying" setup as opposed to motion controlled one was taken for the following reasons: cost; capability to

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easily remove or add weight; better transportability and mobility and finally no permanent infrastructure is required.

The installation is instrumented to make dynamic measurements of the global reaction of the setup and local deformation of the target. Dynamic measurements on the facility considered in this study are the global reaction measurements, frame corners displacement vs. time using hi-speed imagery and finally frame corners acceleration vs. time using accelerometers. In the case of local reaction measurements of the target, the following were measured: displacement vs. time using hi-speed imagery; displacement vs. time using laser displacement sensor and acceleration vs. time using accelerometers mounted on the target.



Figure 1: The experimental setup.

The following are the data obtained from the experimental tests done for a 6-kg TNT explosive mass on 25.4 mm and 19.05 mm Algotuf 400F steel plate thicknesses. The depth of burial was 10 cm taken from the top of the mine to the ground. The plate was located 0.4 m above the ground. Unfortunately, only one experimental value was available for comparison purpose on 19.05-mm plate.

Table1: Results for the 25.4-mm plate thickness and 6-kg explosive mass.

<i>Test number</i>	<i>Total mass of the frame setup, kg</i>	<i>Permanent deflection, m</i>	<i>Dynamic deflection Centre m</i>	<i>Quarter m</i>	<i>Maximum velocity, Centre m/s</i>	<i>Quarter m/s</i>
Exp.1	9581	0.088	0.116	0.089	116	91
Exp.2	9882	0.106	0.130	0.102	135	102
Exp.3	9882	0.086	0.121	0.095	123	95

Table 2: Results for the 19.05-mm plate thickness and 6-kg explosive mass.

<i>Test number</i>	<i>Total mass of the frame setup, kg</i>	<i>Permanent deflection, m</i>	<i>Dynamic deflection Centre m</i>	<i>Quarter m</i>	<i>Maximum velocity, Centre m/s</i>	<i>Quarter m/s</i>
Exp.4	9430	0.145	0.164	-	151	-

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3.0 EMPIRICAL MODEL

3.1 Impulsive loading

The impulse produced from a landmine explosion is mainly the result of detonation products and soil ejecta impacting the target at high velocity. The loading generated from the impulse is characterized by a high pressure during a short response time. Assumption of an impulsive loading is that the duration is much shorter than the natural period of the target structure, and so the exact shape of the pressure-time loading is not as important for the calculation of the target's response as its integral over time. In previous studies, the impulsive assumption along with the Westine model was used [8] on shell elements.

The Westine model was implemented in the DRDC Mine-Pre pre-processor. Mine-Pre software uses ray-tracing algorithms to apply an initial velocity on each individual node based on the impulse obtained from the Westine model and that are function of the mine mass, TNT equivalent, the depth of burial, and the soil density. This assumes that the loading is impulsive, which means that the time of application of the loading should be much shorter than the typical time response of the plate. In the early part of this effort, this approach was used and led to plate deflections much higher (around 40 %) than the ones experimentally measured. To account for this discrepancy, modifications of the Westine model loading are investigated, mainly, by assuming a non-impulsive loading that has a certain time history over a long period of time (mainly 5-6 ms). Different time-distribution formulas with different parameters were then investigated.

3.2 Non-impulsive loading

As discussed previously, it was suggested that the discrepancy between experimental results and simulations was due to the non-impulsive nature of the loading. Rather, it should be applied as a pressure-time history for which the specific impulse is given by the Westine predictions [8]. Remember that the specific impulse (I_s) is given by:

$$I_s = \int_0^{t_A} P(t) dt \quad (1)$$

Where $P(t)$ is the pressure and t_A is the time of application of the loading. The value of I_s is given by Westine formula and depends on the depth of burial, standoff distance, explosive mass, type of explosive and the distance from detonation [8]. There is an infinite number of possibilities and combinations of t_A and $P(t)$ that can give the right solution. The goal of this work is to narrow down these possibilities and determine a "working" loading that can be used for design purposes.

To our knowledge, it is not possible at the moment to measure experimentally the pressure time history applied on a plate due to the mine blast and ejecta and therefore, the shape of the pressure-time history has to be quite arbitrarily chosen. However, there are a few constraints that allow making an educated guess of this shape. First, the time of application t_A should be on the order of a few milliseconds because this is the time that the deformation lasts (around 5-6 ms); secondly, the limit of $P(t)$ when t tends to t_A should be 0 and finally, the equation should be relatively simple and smooth for numerical implementation.

A number of pressure-loading profiles $P(t)$ were considered but the one that showed an agreement with the experimental results is given in Equation 2. The integral over time of this equation should give the same impulse calculated by Westine over target geometry.

$$P(t) = P_{HSF} \sin\left(\pi \frac{t}{\Delta t}\right) \left(1 - \frac{t}{\Delta t}\right) \exp\left(-\alpha \frac{t}{\Delta t}\right) \quad (2)$$

In Equation 2, Δt characterizes the duration of the event; P_{HSF} is normalization constant introduced to get the specific impulse from the Westine model and α is a non-dimensional constant. The half-sin Friedlander shape given in this equation consists of a Friedlander function multiplied by a sin that represents pressure distribution at a given time (t) over the total area of the target. This model can be described as a static model since the loading is applied at the same time over the entire plate (target) and do not depends on the time of arrival of the blast. The value of the parameters for every loading considered in this study is given in Table 3.

Table 3: The parameter values simulated for the Half-sin Friedlander model.

Loading cases	α	Δt
HsinF1	0.25	1.00 ms
HsinF2	0.50	1.00 ms
HsinF3	0.25	1.50 ms
HsinF4	0.25	1.75 ms
HsinF5	0.25	2.00 ms
HsinF6	0.25	2.50 ms

4.0 NUMERICAL MODEL

The simulations were performed with the LS-DYNA finite element hydrocode [17]. This code has very good contact capability, and contains many features such as a library of material models, element formulations, boundary conditions, etc., making it a very good choice for the simulations performed in this study. Throughout this work, the Lagrangian formulation was utilized.

4.1 Geometry and mesh

The CAD model of the setup is shown in Figure 2. The dimensions were taken from the real experimental setup. It was made of three parts namely, the support frame, the plate and the bolts. The geometry of the support frame was simplified compared to the real setup because it was assumed that it did not suffer from any deformations. Thus, only the edge and opening sizes were important in the present analysis. Non-structural masses were added to the support frame to make sure the whole setup has the right weight.

Only a quarter of the whole problem was simulated taking advantage of the symmetry of the system. Boundary conditions on the symmetry planes were implemented accordingly. The plate thicknesses considered were 25.4 mm (1.00 inch) and 19.05 mm (0.75 inch). The CAD model was meshed using solid elements having an approximate edge size of 7 mm. The frame and the steel plate were made respectively of 84,476 and 76,070 solid elements, whereas the bolts were meshed using 512 and 448 shell elements for the 25.4 mm and 19.05 mm model respectively.

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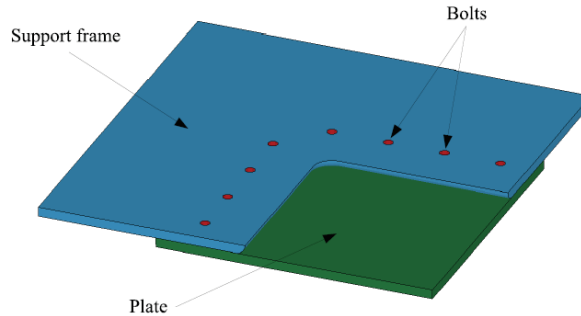


Figure 2: FEM of the plate support (25.4-mm plate thickness).

4.2 Material properties

The frame and the bolts were assumed rigid (no deformation) during the mine explosion. Therefore, they were modelled with a rigid material model in LS-DYNA. The density given to these parts was the density of steel, which is shown in Table 4. For the steel plate, the type of steel used was Algotuf 400F. Because the maximum strain-rate level reached in simulations was approximately 320 s⁻¹, which is relatively low, the strain-rate effects were neglected and a simple elastic-plastic model was used. The material parameters used in the simulation are presented in Table 4. These data are collected from experimental tests. No fracture criterion was used since it was known experimentally that the plate would not fail.

Table 4: Material properties for the Algotuf 400F steel used in the FEM.

Material properties	Algotuf 400F steel
Density, kg/m ³	7870
Young modulus, MPa	210 x 10 ³
Poisson's ratio	0.3
Yield stress, MPa	1000
Tangent modulus, MPa	752.6

5.0 RESULTS

5.1 25.4-mm thick plate

Figure 3 shows plate centre and quarter deflection vs. time for the six scenarios listed in Table 3. A comparison between the experimental and the numerical dynamic and permanent deflections shows that HSinF6 is the closest scenario to the experimental data. The α parameter has no effect on the computed deflection (HSinF1 vs. HSinF2). As the duration of the event (Δt) increases from 1 ms to 2.5 ms, the maximum permanent deflection decreases. This can be explained by the total energy transferred from the buried-mine (a fixed value) to the plate being smeared over a longer period of time, which results in lower pressure values.

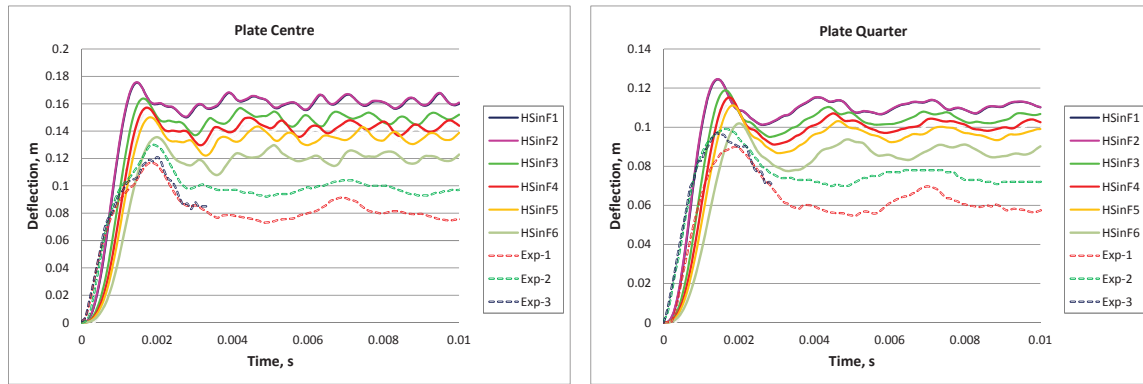


Figure 3: Plate-centre (Left) and quarter (Right) deflection vs. time on 25.4 mm plate.

5.1 19.05-mm thick plate

Table 5 shows the dynamic and permanent center deflection for the 5 scenarios listed in Table 3. As for the 25.4-mm case, the scenario that best matches the experimental data is the HsinF6 having less than 15% relative error relative to the experimental result.

Table 5: Plate center dynamic and permanent deflection (19.05 mm)

<i>Test number</i>	<i>Dynamic deflection, m</i>	<i>Relative error, %</i>	<i>Permanent deflection, m</i>	<i>Relative error, %</i>
HsinF1	0.228	39.0	0.212	46.2
HsinF2	0.228	39.0	0.212	46.2
HsinF3	0.215	31.1	0.199	37.2
HsinF4	0.208	26.8	0.191	31.7
HsinF5	0.199	21.3	0.183	26.2
HsinF6	0.181	10.4	0.167	15.2
Exp.4	0.164	-	0.145	-

$$\% \text{ relative error} = (\text{Num} - \text{Exp}) * 100 / \text{Exp}$$

5.2 Initial global vertical velocity of the setup

The initial global vertical velocities obtained for the two 25.4-mm and 19.05-mm thick plate models as well as for the experimental results are shown respectively in Figure 4 and Figure 5. To calculate the numerical initial velocities of the setup, a ballistic trajectory was assumed and a second order polynomial curve was fit on the vertical displacement versus time curve. The second order curves represent the displacement as a function of the initial acceleration and initial velocity ($z = a_0 t^2 + V_0 t + z_0$). The first 2 ms were not taken into account when the ballistic trajectory was computed numerically as what was done for the experimental tests. Actually, the first 2 ms of the setup displacement could not be filmed using high speed video cameras due to the soil ejecta, and therefore were not available to compute the experimental initial velocity.

In Figures 4 and 5, the horizontal lines are the experimental values, whereas the columns are those of the numerical models. The computed Half-Sin Friedlander velocities of all scenarios are in the same order of magnitude and within the experimental variation for both 25.4-mm and 19.05-mm thick plate. From these

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comparisons it is suggested to use the HsinF model with the following parameters ($\alpha = 0.25$ and $\Delta t = 2.5$ ms) corresponding to HsinF6 case to conduct future studies on the effects of mine blast on targets.

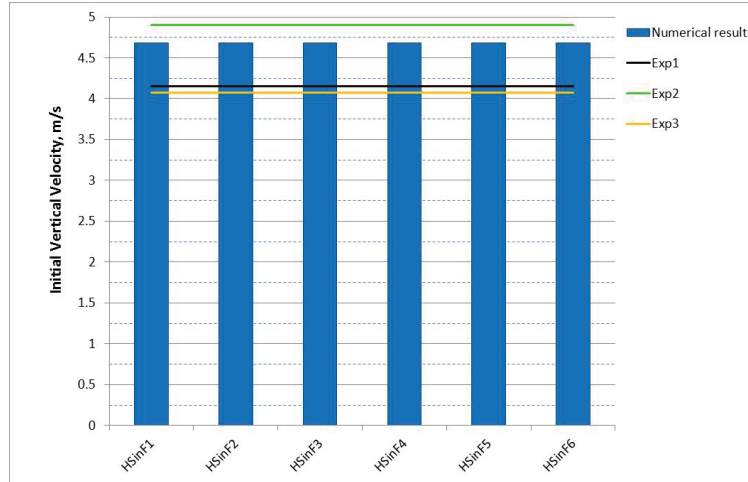


Figure 4: The experimental and numerical maximum velocity at center of mass (25.4 mm).

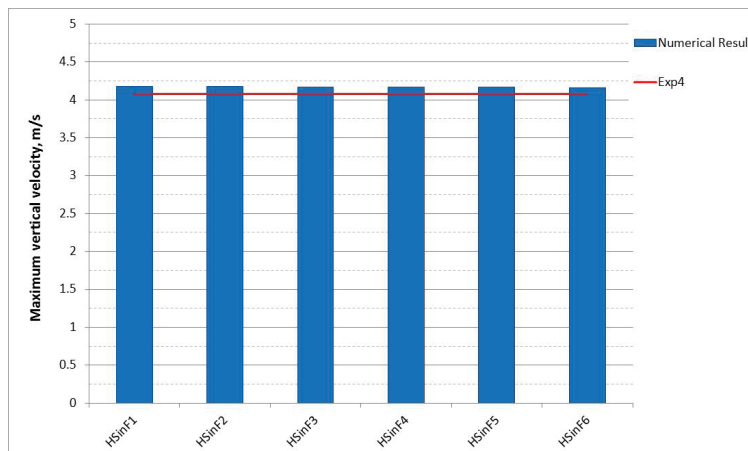


Figure 5: The experimental and numerical maximum velocity at center of mass (19.05 mm).

6.0 CONCLUSION

In this effort, the assumption that the loading from buried landmines is impulse was critically investigated and many non-impulsive time-distribution formulas were investigated to generate the initial loadings that can be applied on a target that is meshed using solid elements. The specific impulse of the pressure-time model was given by the Westine predictions. The final proposed model is a half-sin Friedlander equation that represents pressure distribution at a given time (t) over a target. The parameters of this pressure model were

validated using experimental data from a 6 kg TNT charge denoted under a plate of 25.4 mm thickness and under a plate of 19.05 mm thickness. Future work will include the validation of the empirical model with other types of landmines.

REFERENCES

- [1] Schneck, LTC W. III, *History of the Landmine*, unpublished manuscript.
- [2] Morris., B.L., *Analysis of Improved Crew Survivability in Light Vehicles Subjected to Mine Blast/Volumes 1 & 2*. Technical Report SwRI Project No. 06-5095, US Army Belvoir Research, Development and Engineering Center, Fort Belvoir, Virginia, December 1993. UNCLASSIFIED.
- [3] Tremblay, J.E., *Impulse on blast deflectors from a landmine explosion*. DREV Technical memorandum, DREV-TM-9814, 31 pages, 1998, UNCLASSIFIED.
- [4] Bergeron, D.M. and Tremblay, J.E., *Canadian research to characterize mine blast output*. 16th International Symposium on Military Aspects of Blast and Shock, Oxford, UK, 2000.
- [5] Bergeron, D.M., Walker, R.A. and Coffey, C.G., *Mine Blast Characterization - 100 gram C4 Charges in Sand*. Suffield Report 668, June 1998.
- [6] TM 5-855-1, *Fundamentals of Protective Design for Conventional Weapons*. Department of the Army, US Army Corps of Engineers, Washington. 1989, UNCLASSIFIED
- [7] Department of the Army, *Fundamentals of protective design for conventional weapons*. TM 5-855-1, US Army, November, 1986.
- [8] Westin, P.S, Morris, B.L. Cox, P.A. and Polch. E.Z., *Development of computer program for floor plate response from land mine explosions*. Technical Report No. 13045, US Army Tank-Automotive Command, Warren, MI, January, 1985. UNCLASSIFIED.
- [9] Williams, K., McClennan, S., Durocher, R., St-Jean, B. and Tremblay, J., *Validation of a Loading Model for Simulating Blast Mine Effects on Armoured Vehicles*. 7th Ls-Dyna Users Conference, 2002.
- [10] Tremblay, J.E., Bergeron, D.M. and Gonzalez, R., *Protection of Soft-Skinned Vehicle Occupants from Landmine Effects*. KTA 1-29 Technical Report, 1998.
- [11] Fortier, C., Dumas, S., Durocher, R., St-Jean, B., Bourget, D. *Effects of Terrorist-Like Explosions on Ships and Personnel*. DREV TR 2001-226. 2002, UNCLASSIFIED
- [12] NATO STANAG 4569, *Protection levels for occupants of logistic and light armoured vehicles*. AC/225-D/1463, May 1999.
- [13] NATO AEP-55, Volume 2, 1st Edition, *Procedures for Evaluating the Protection Level of Logistic and Light Armoured Vehicles – for Mine Threat*. May 2006 (UNCLASSIFIED)
- [14] Bergeron, D.M and Gonzalez, R., *Towards a Better Understanding of Land Mine Blast Loading*. TTCP TP-1 Terminal effects, KTA 1-34 report, 2004.
- [15] Bues, R., Hlady, S.L. and Bergeron, D.M., *Pendulum Measurement of Land Mine Blast Output, Volume 1: Theory and Implementation*. Technical Report TR 2001-200, DRDC – Suffield, 2001.
- [16] Toussaint G., Durocher R., Bouamoul A., Vallée A. and St-Jean B. *Assessment of an experimental method and two loading methods used to measure and simulate the effects of buried charge*, International Symposium on Ballistics, 22-26 April 2013.
- [17] Hallquist, J. *LS-DYNA User's Manual –Version 971*. Livermore Software Technology Corporation, Livermore, CA, 2010.